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Procedia - Social and Behavioral Sciences 43 (2012) 530 – 539

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**Procedia**  
Social and Behavioral Sciences

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8<sup>th</sup> International Conference on Traffic and Transportation Studies  
Changsha, China, August 1–3, 2012

## Delay Modeling of Ped-Veh System Based on Pedestrian Crossing at Signalized Intersection

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### Abstract

The different conflicts between pedestrian and vehicle induce traffic delay and decrease urban the efficiency of road traffic at a certain extent. Rare researchers pay their attentions to the pedestrian and vehicle conflict system as whole. Based on characteristics and conflict scenes analysis of pedestrian and vehicle behaviors at isolated signalized intersection, 4 types of ped & veh behavior rules are described, the ped-veh inference courses by once and twice pedestrian crossing are expatiated, then, 3 delay models of ped-veh system are established. Finally, taken advantage of VISSIM software and big intersection in Beijing as example, a simulation case is calculated. Data shows that: due to twice pedestrian crossing, the system delays are 14.3% and 7.4% less than once one at a.m. and p.m. peak time separately.

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**Keywords:** pedestrian-vehicle conflict system; types of pedestrian crossing; delay model; isolated signalized intersection; VISSIM simulation

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### 1. Introduction

The fast and long distance trips increased by high urban mechanization level improve the travel condition. The short distance trips including foot as representative of slow traffic system joins long

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travels together. They connect each other in time dimension and cause the vehicle-pedestrian conflict in space dimension. Then, delays are produced. It is a good method to giving attentions to pedestrian safety, traffic efficiency, road resource that continually optimizing the pedestrian crossing facilities at where the conflicts often happen, such as isolated signalized intersection.

At large signalized intersection, there are traffic lights for pedestrian, long distance to crossing, heavy traffic flow, lots of conflict and low intersection operational quality. Worse, the time for pedestrian to finish his or her crossing is often insufficient. he or she has to evade or obtrude the vehicle at lanes. On the other hand, the signalized control can avoid the conflicts between straight vehicle flow and pedestrian. It cannot reduce the conflicts between right-turn vehicle flow and pedestrian at entrance way except the right-turn traffic light, and the conflicts between left-turn vehicle flow and pedestrian at exit way due to the short crossing time. The forms of pedestrian crossing are once and twice.

About the conflicts studies, the foreign researchers prefer describing the both behaviors at crosswalk. Lord (2006) considered it is more conflicts at T intersections than normal intersection. Knodler *etc* (2006) analyzed the reactions of driver and pedestrian to amber signalized among signalized phase and their influence. Schattler *etc* (2007) aimed at the influence of count-down signalized to pedestrian and driver. It detailed the reactions at different signalized stages and confirmed that that type signalized can enhance safety at crosswalks and no vehicle risks added by comparing 3 count-down signals. Hagiwara *etc* (2010) investigated the interval time of right-turn vehicle and pedestrian arriving at the crosswalk, draw the space-time distributing chart in order to describing the vehicle and pedestrian behaviors at the conflict area, Kaparias *etc* (2010) depicted their microcosmic behaviors during the conflicts combining vehicle-vehicle conflict analysis method and space-time intervals, safety, complication. The domestic researchers prefer analyzing the conflicts between turning vehicle and pedestrian. Su *etc* (2008) obtained the data about right-turn vehicle and pedestrian conflicts at signalized intersection, such as the vehicle speed before/after the conflict, then established the speed statistical model of right-turning vehicle at different positions to conflict area. Lee *etc* (2008) distinguished the relationship of pedestrian speed and volume, set up the pedestrian simulation model on various directions. Chen *etc* (2010) considered the factors of pedestrian crossing, established the duality logic model of pedestrian abiding intersection signalized. It is also suggested that adjusting the position of fences could advance the possibility of pedestrian abiding signalized obviously. About delay model description, most researchers focus on pedestrian or vehicle delay separately. Ishaque and Noland (2008a) considered the vehicle type, traffic volume, simulated the vehicle and pedestrian delay at different signalized timing. Wang and Tian (2010) divided pedestrian twice crossing delay into 3 parts, green light delay, green flash delay and red stop time, and illustrated the types of delay. Li Q F *etc* (2005) explained the pedestrian delay of different directions at signalized intersection in Xi'an, China. They proved that pedestrian could still have delay when he cross the street even the light was green or he totally ignored the red light because people arrived unevenly. Most of studies ignored the conflicts caused by short crossing time of pedestrian at big signalized intersection. It may be a right way to judge the impact of once or twice pedestrian crossing to traffic in the form of veh-ped system. Based on the pedestrian and vehicle behavior factors at signalized intersection, conflict mechanism is analyzed. The conflict areas and types are defined, pedestrian and vehicle behaviors judging rules are radicated separately. With the help of signalized timing Figures of 3 and 4 phases, veh-ped delay models based on pedestrian crossing are established. After demarcating the relative factors, simulation aims at an intersection with 4 signalized phases in Beijing. Veh-ped system delays at the condition of pedestrian once or twice crossing are calculated to validate these models.

## 2. Pedestrian and vehicle conflict mechanism

The type of pedestrian crossing is decided by pedestrian light at link center. If there is, it is once one. if

not, it is twice once. Pedestrian totally obeys the traffic signalized are assumed.

### 2.1 Pedestrian and vehicle behavior factors

The pedestrian behavior to conflict is described 3 types, Park Yield(PY), Not Yield(NY) and No Conflict(NC). The vehicle behavior to conflict is described 4 types, Soft Yield(SY), Hard Yield(HY), Not Yield(NY) and No Conflict. At same time, the pedestrian is divided into 2 types, Looking Right(LR) and Looking Left(LL), according the vehicle directions. Accordingly, the conflict area is divided into LR type and LL type.

Due to red pedestrian lights, people wait to cross the street near the crosswalk and gradually congregated. Same direction pedestrian tend to choosing the close position(Yang *etc*, 2008). We assume most pedestrian choose the right part of crosswalk, every obey traffic rules strictly, ignore the conflict among the pedestrian. On the other hand, the stop line is not only a symbol for vehicle when its traffic light turns red and also an ambit for vehicle yielding the pedestrian when traffic light is just turn green and pedestrian do not achieve his crossing yet. We assume that the hard yield vehicle head is just at the stop line, and soft yield vehicle position is related to traffic speed, lane with and other factors. The stop line is painted at the entrance way, not at the exit way. So vehicle at exit way judge its behavior by relative position with pedestrian.

### 2.2 Conflict mechanism analysis

Assume there are  $n$  lane at westbound of a large intersection. width of single lane is  $l_m$ , entrance lane (west to east) number is  $n_2$ , exit lane (east to west) number  $n_1$ ,  $n=n_1+n_2$ , 且  $n \geq 1$ ,  $n$ ,  $n_1$ ,  $n_2 \in N$ . In this paper,  $n_1=n_2=n/2=3$ , shown as Fig.1. The width of isolation bond is  $B_0$ . the link width is  $L_m$ , and  $L_m=n l_m+B_0=(n_1+n_2)l_m+B_0$ . So the pedestrian foot distance,  $D_a$  is equal to crosswalk length,  $H_0$ , namely  $D_a=H_0=L_m$ , the crosswalk width,  $h_0$  is equal to distance of vehicle across the conflict area,  $D_b$ , namely  $h_0=D_b$ .

Take the middle line of isolation bond as  $x$  axes, crosswalk center side as  $y$  axes to set reference frame.  $x, y$  axis meet at origin point(0,0). Pedestrian coordinate is  $(x_a, y_a)$ , forehead midpoint of vehicle is  $(x_b, y_b)$ .  $Ln_k (k \in [-n_2, n_1])$  is lane number.  $Ln_k$  is correlative with  $y_a, y_b$ .

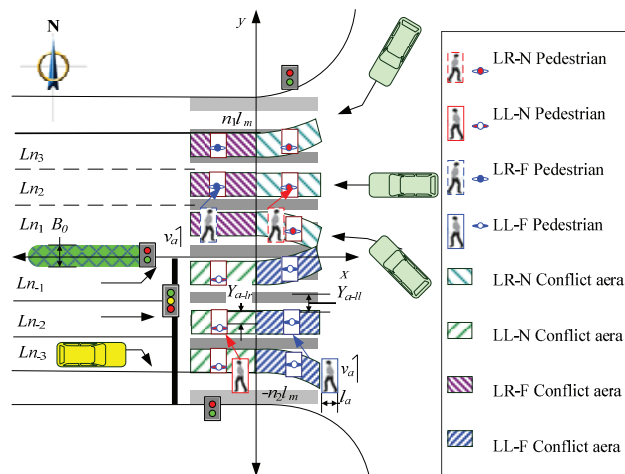


Fig. 1. Four conflict types between pedestrian and vehicle at crosswalk of westbound of signalized intersection

The scope of crosswalk is the rectangle of  $\{(x, y)|x \in [-h_0/2, h_0/2], y \in [-n_2l_m - B_0/2, n_1l_m + B_0/2]\}$ . Pedestrian crossing course is the point  $(x_a, y_a)$  moving between  $[x_a, -n_2l_m - B_0/2]$  and  $[x_a, n_1l_m + B_0/2]$ . Vehicle must avoid conflict with pedestrian when the point  $(x_b, y_b)$ ,  $(y_b \in [-(n_2-1/2)l_m - B_0/2, (n_1-1/2)l_m + B_0/2])$  moving between  $[-h_0/2, y_b]$  and  $[h_0/2 + L_b, y_b]$  (if  $y_b \in [-(n_2-1/2)l_m - B_0/2, 0]$ ) or  $[h_0/2, y_b]$  and  $[-(h_0/2 + L_b), y_b]$  (if  $y_b \in [0, (n_1-1/2)l_m + B_0/2]$ ).

Due to accumulation of pedestrian red light, lots of people at the right part of crosswalk and few at the left part. When the light turn red, there are 2 directions pedestrian at all 4 quadrants. According to the foot direction, pedestrian are divided into 2 forms, Upward to Downward (U2D) and Downward to Upward (D2U) pedestrian. U2D conflicts with traffic at firstly entrance way and then exit way, U2D is inverse.

### 2.3 Conflict area, conflict types and conflict scenes

According to the vehicle directions and pedestrian foot order, the conflict area can defined as 4 types, Looking Left- Near (LL-N), Looking Left-Far (LL-F), Looking Right- Near (LR-N), Looking Right -Far (LR-F).

At the reference frame, U2D and D2U pedestrian  $(x_a, y_a)$  and their types shown as the table 1.

Table 1. Relationships between types and coordinates of pedestrian at crosswalk of westbound of signalized intersection

Foot direction	ya scale	xa scale			
		LL-N	LL-F	LR-N	LR-F
U2D	$[-n_2l_m - B_0/2, 0]$	$[-h_0/2, 0]$	$(0, h_0/2]$	-	-
	$[0, n_1l_m + B_0/2]$	-	-	$(0, h_0/2]$	$[-h_0/2, 0]$
D2U	$[0, n_1l_m + B_0/2]$	$(0, h_0/2]$	$[-h_0/2, 0]$	-	-
	$[-n_2l_m - B_0/2, 0]$	-	-	$[-h_0/2, 0]$	$(0, h_0/2]$

### 3. Behavior judgment rules

Considering the occupy conflict area rules, pedestrian at same position of crosswalk share the same behavior judgment rules.

For U2D, vehicles at entrance way refer the stop line as hard yield line at LL-N and LL-F area, while vehicles at exit way have no such reference at LR-N and LR-F areas. So, U2D pedestrian crossing has 4 behavior judgment rules. On the other hand, due the turn flow, U2D has same rules but different parameters when crossing the same conflict area and different lanes.

To eliminating the turn vehicle and the bend factor,  $c_{ab}$  is the bend distance between pedestrian and vehicle and relative with  $(x_a, y_a)$  and  $(x_b, y_b)$ . For the straight vehicle,  $c_{ab} = |x_b - x_a|$ . if  $x_b \geq 0$ ,  $(c_{ab} + x_a)$  is equal to  $x_b$  which U2D at LL-F and LR-N areas; if  $x_b < 0$ ,  $(-c_{ab} + x_a)$  is equal to  $x_b$  which U2D at LL-N and LR-F.  $\theta$  is the bend quotiety and used to judge the pedestrian and vehicle at same or not and related with turning vehicle position and radius.  $(x'_b, y'_b)$  is replaced  $(x_b, y_b)$  at the judgment group, namely  $((c_{ab} + x_a), \theta y_b, x_b \geq 0)$  or  $((-c_{ab} + x_a), \theta y_b, x_b < 0)$ .

So,

$$Ln_a = \frac{y_a}{|y_a|} \left\lceil \frac{|y_a| - B_0/2}{l_m} \right\rceil, \quad Ln_b = \frac{y_b}{|y_b|} \left\lceil \frac{|\theta y_b| - B_0/2}{l_m} \right\rceil \quad (1)$$

where  $\lceil y \rceil$  is up integer function,  $|y_a| \leq |Ln_a l_m| + B_0/2$ ,  $|\theta y_b| \leq |Ln_b l_m| + B_0/2$ .

Only when  $Ln_a = Ln_b = Ln_K$ , the conflict may happen and the pedestrian and vehicle must follow the behavior judgment rules.

(1) Pedestrian park yield judgment group  $S(PY)$ 

where if pedestrian is at the 1<sup>st</sup> guardant,

$$S_2(PY)_1 = \{(x_a, y_a), (x_b, y_b) \mid (h_0/2 + Y_0) < c_{ab} + x_a \leq (l_m v_b / v_a + h_0/2 + Y_0), (c_{ab} + x_a)\theta y_b > 0 \\ \text{or} \mid c_{ab} + x_a \leq (h_0/2 + L_b) \text{ and } \mid c_{ab} + x_a \leq (h_0/2 + Y_0) \mid y_a \mid = \mid L_{n_k} l_m \mid + B_0/2, \\ x_a y_a \geq 0, \mid \theta y_b \mid = \mid L_{n_k} \mid - 1/2, k \in [0, n_1], k \in N\}$$

If pedestrian is at the 2<sup>nd</sup> guardant,

$$S_2(PY)_2 = \{(x_a, y_a), (x_b, y_b) \mid Y_0 < c_{ab} + x_a \leq (l_m v_b / v_a + Y_0), (c_{ab} + x_a)\theta y_b > 0 \text{ or } \mid c_{ab} + x_a \leq Y_0, (c_{ab} + x_a)\theta y_b > 0 \text{ or} \\ \mid -c_{ab} + x_a \leq (h_0/2 + L_b), (-c_{ab} + x_a)\theta y_b < 0 \mid y_a \mid = \mid L_{n_k} l_m \mid + B_0/2, x_a y_a < 0,$$

It pedestrian at the 3<sup>rd</sup> guardant,

$$S_2(PY)_3 = \{(x_a, y_a), (x_b, y_b) \mid (h_0/2 + Y_0') < -c_{ab} + x_a \leq (l_m v_b / v_a + h_0/2 + Y_0'), (-c_{ab} + x_a)\theta y_b > 0 \text{ or} \\ \mid -c_{ab} + x_a \leq (h_0/2 + L_b) \text{ and } \mid -c_{ab} + x_a \leq (h_0/2 + Y_0') \mid y_a \mid = \mid L_{n_k} l_m \mid + B_0/2, x_a y_a \geq 0, \\ \mid \theta y_b \mid = \mid L_{n_k} \mid - 1/2, k \in [-n_2, 0], k \in N\}$$

If pedestrian is at the 4<sup>th</sup> guardant,

$$S_2(PY)_4 = \{(x_a, y_a), (x_b, y_b) \mid Y_0' < -c_{ab} + x_a \leq (l_m v_b / v_a + Y_0'), (-c_{ab} + x_a)\theta y_b > 0 \text{ or} \\ \mid -c_{ab} + x_a \leq Y_0', (-c_{ab} + x_a)\theta y_b > 0 \text{ or } \mid c_{ab} + x_a \leq (h_0/2 + L_b), (c_{ab} + x_a)\theta y_b < 0 \\ \mid c_{ab} + x_a \leq (h_0/2 + L_b), (c_{ab} + x_a)\theta y_b < 0 \mid \theta y_b \mid = \mid L_{n_k} \mid - 1/2, k \in [-n_2, 0], k \in N\}$$

Thus,

$$S_2(PY) = S_2(PY)_1 \cup S_2(PY)_2 \cup S_2(PY)_3 \cup S_2(PY)_4$$

If pedestrian  $(x_a, y_a)$  and vehicle  $(x_b, y_b)$  meet the group  $S_2(PY)$ , pedestrian yields the vehicle. if not, pedestrian crosses the street.

(2) Vehicle soft yield judgment group  $S_2(SY)$ 

Where, if pedestrian is at the 1<sup>st</sup> guardant,

$$S_2(SY)_1 = \{(x_a, y_a), (x_b, y_b) \mid (h_0/2 + Y_0) < c_{ab} + x_a \leq (l_m v_b / v_a + h_0/2 + Y_0), (c_{ab} + x_a)\theta y_b > 0, x_a y_a \geq 0 \\ \mid (L_{n_k} \mid - 1) l_m \mid + B_0/2 < \mid y_a \mid < \mid L_{n_k} \mid l_m \mid + B_0/2, \mid \theta y_b \mid = \mid (L_{n_k} \mid - 1/2) l_m \mid + B_0/2, k \in [0, n_1], k \in N\}$$

If pedestrian is at the 2<sup>nd</sup> guardant,

$$S_2(SY)_2 = \{(x_a, y_a), (x_b, y_b) \mid Y_0 < c_{ab} + x_a \leq (l_m v_b / v_a + Y_0), (c_{ab} + x_a)\theta y_b > 0, x_a y_a < 0 \\ \mid (L_{n_k} \mid - 1) l_m \mid + B_0/2 < \mid y_a \mid < \mid L_{n_k} \mid l_m \mid + B_0/2, \mid \theta y_b \mid = \mid (L_{n_k} \mid - 1/2) l_m \mid + B_0/2, k \in [0, n_1], k \in N\}$$

It pedestrian at the 3<sup>rd</sup> guardant,

$$S_2(SY)_3 = \{(x_a, y_a), (x_b, y_b) \mid (h_0/2 + Y_0') < -c_{ab} + x_a \leq (l_m v_b / v_a + h_0/2 + Y_0'), (-c_{ab} + x_a)\theta y_b > 0, x_a y_a \geq 0 \\ \mid (L_{n_k} \mid - 1) l_m \mid + B_0/2 < \mid y_a \mid < \mid L_{n_k} \mid l_m \mid + B_0/2, \mid \theta y_b \mid = \mid (L_{n_k} \mid - 1/2) l_m \mid + B_0/2, k \in [-n_2, 0], k \in N\}$$

If pedestrian is at the 4<sup>th</sup> guardant,

$$S_2(SY)_4 = \{(x_a, y_a), (x_b, y_b) \mid Y_0' < -c_{ab} + x_a \leq (l_m v_b / v_a + Y_0'), (-c_{ab} + x_a)\theta y_b > 0, x_a y_a < 0 \\ \mid (L_{n_k} \mid - 1) l_m \mid + B_0/2 < \mid y_a \mid < \mid L_{n_k} \mid l_m \mid + B_0/2, \\ \mid \theta y_b \mid = \mid (L_{n_k} \mid - 1/2) l_m \mid + B_0/2, k \in [-n_2, 0], k \in N\}$$

Thus,

$$S_2(SY) = S_2(SY)_1 \cup S_2(SY)_2 \cup S_2(SY)_3 \cup S_2(SY)_4$$

If vehicle  $(x_b, y_b)$  meet group  $S_2(SY)$ , vehicle yields the pedestrian. If not, vehicle adopts other behavior: hard yield or go ahead.

(3) Vehicle hard yield judgment group  $S_2(HY)$ 

if pedestrian is at the 1<sup>st</sup> guardant,

$$S_2(HY)_1 = \{(x_a, y_a), (x_b, y_b) \mid (h_0/2 + Y_0) < c_{ab} + x_a \leq (l_m v_b / v_a - L_b), (c_{ab} + x_a)\theta y_b > 0, x_a y_a \geq 0$$

$$(|Ln_K|-1)l_m+B_0/2 < |y_a| < |Ln_K|l_m+B_0/2, |\theta y_b| = (|Ln_k|-1/2)l_m+B_0/2, k \in [0, n_1], k \in N \} \quad (12)$$

If pedestrian is at the 2<sup>nd</sup> guardant,

$$S_2(HY)_2 = \{(x_a, y_a), (x_b, y_b) \mid |c_{ab} + x_a| \leq (l_m v_b / v_a - h_0 / 2 - Y_0), (c_{ab} + x_a)\theta y_b > 0, x_a y_a < 0 \\ |(|Ln_K|-1)l_m+B_0/2 < |y_a| < |Ln_K|l_m+B_0/2, |\theta y_b| = (|Ln_k|-1/2)l_m+B_0/2, k \in [0, n_1], k \in N \} \quad (13)$$

It pedestrian at the 3<sup>rd</sup> guardant,

$$S_2(HY)_3 = \{(x_a, y_a), (x_b, y_b) \mid (h_0 / 2 + Y_0') < -c_{ab} + x_a \leq (l_m v_b / v_a - L_b), (-c_{ab} + x_a)\theta y_b > 0, x_a y_a \geq 0 \\ |(|Ln_K|-1)l_m+B_0/2 < |y_a| < |Ln_K|l_m+B_0/2, |\theta y_b| = (|Ln_k|-1/2)l_m+B_0/2, k \in [-n_2, 0], k \in N \} \quad (14)$$

If pedestrian is at the 4<sup>th</sup> guardant,

$$S_2(HY)_4 = \{(x_a, y_a), (x_b, y_b) \mid Y_0' < -c_{ab} + x_a \leq (l_m v_b / v_a - h_0 / 2 - Y_0'), (-c_{ab} + x_a)\theta y_b > 0, x_a y_a < 0 \\ |(|Ln_K|-1)l_m+B_0/2 < |y_a| < |Ln_K|l_m+B_0/2, |\theta y_b| = (|Ln_k|-1/2)l_m+B_0/2, k \in [-n_2, 0], k \in N \} \quad (15)$$

$$S_2(HY) = S_2(HY)_1 \cup S_2(HY)_2 \cup S_2(HY)_3 \cup S_2(HY)_4 \quad (16)$$

If vehicle  $(x_b, y_b)$  meet group  $S_2(HY)$ , vehicle yields the pedestrian. If not, vehicle adopts other behavior: soft yield or go ahead.

(4) Vehicle and pedestrian no conflict judgment group  $S_2(NC)$

Where, if pedestrian is at the 1<sup>st</sup> guardant,

$$S_2(NC)_1 = \{(x_a, y_a), (x_b, y_b) \mid -c_{ab} + x_a > L_b, (-c_{ab} + x_a)\theta y_b < 0, x_a y_a \geq 0 \} \quad (17)$$

If pedestrian is at the 2<sup>nd</sup> guardant,

$$S_2(NC)_2 = \{(x_a, y_a), (x_b, y_b) \mid -c_{ab} + x_a > (h/2 + L_b), (c_{ab} + x_a)\theta y_b < 0, x_a y_a < 0 \} \quad (18)$$

It pedestrian at the 3<sup>rd</sup> guardant,

$$S_2(NC)_3 = \{(x_a, y_a), (x_b, y_b) \mid -c_{ab} + x_a > L_b, (-c_{ab} + x_a)\theta y_b < 0, x_a y_a \geq 0 \} \quad (19)$$

If pedestrian is at the 4<sup>th</sup> guardant,

$$S_2(NC)_4 = \{(x_a, y_a), (x_b, y_b) \mid -c_{ab} + x_a > (h/2 + L_b), (c_{ab} + x_a)\theta y_b < 0, x_a y_a < 0 \} \quad (20)$$

Thus,

$$S_2(NC) = S_2(NC)_1 \cup S_2(NC)_2 \cup S_2(NC)_3 \cup S_2(NC)_4 \quad (21)$$

If vehicle  $(x_b, y_b)$  meet group  $S_2(NC)$ , vehicle go ahead without conflict. If not, vehicle adopts other behavior: soft yield or hard yield.

The 4 behavior judgment group  $S_2$

$$S_2 = \{S_2(PY), S_2(SY), S_2(HY), S_2(NC)\} \quad (22)$$

Based on the judgment rules, delay are analyzed and modeled. It is used to evaluated the link operation efficiency.

#### 4. Delay analysis of different pedestrian crossing types

(1) pedestrian and vehicle delays at once pedestrian crossing. At large signalized intersection, vehicle and pedestrian are controlled by the traffic lights. The conflicts are related with the signal timing (Fig. 2).

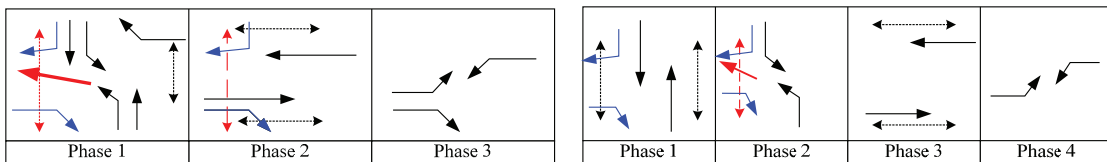


Fig. 2. Pedestrian Delay (a) 3 signal phases (westbound)

(b) 4 signal phases (westbound)

In Fig. 2(a), at phase 1, pedestrian of westbound conflict with right turn vehicle of westbound and

northbound, and left turn vehicle of southbound. They cannot finish the crossing this green light at large intersection. So they will conflict with straight vehicle of westbound and eastbound at phase2. Both of them accord the judge rule  $S_2$  to finish the course and course the delay.

In Fig. 2(b), at phase 1, pedestrian of westbound conflict with right turn vehicle of westbound and northbound. They can not finish the crossing this green light at large intersection. So they will conflict with left turn vehicle of southbound 2. Both of them accord the judge rule  $S_2$  to finish the course and course the delay.

## (2) pedestrian and vehicle delays at twice pedestrian crossing

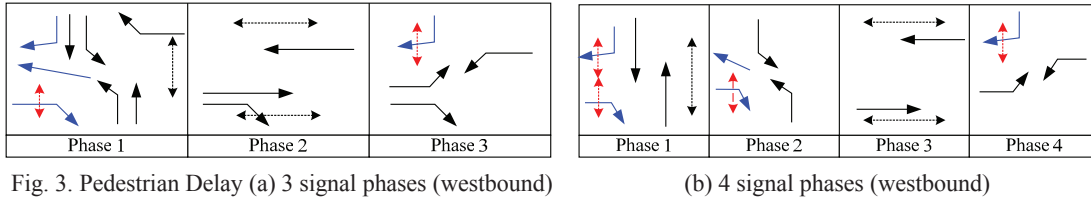


Fig. 3. Pedestrian Delay (a) 3 signal phases (westbound)

(b) 4 signal phases (westbound)

In Fig. 3(a), at phase 1, pedestrian of westbound conflict with right turn vehicle of westbound. At phase 3, pedestrian of westbound conflict with right turn vehicle of northbound. The conflict between pedestrian and left turn vehicle of southbound is largely decreased, but the pedestrian delay is increased.

In Fig. 3(b), at phases 1,2 and 4, pedestrian of westbound conflict with right turn vehicle. The conflict between pedestrian and left turn vehicle of southbound is largely decreased and time for pedestrian crossing is added.

## 5. Delay model

Pedestrian  $i$  have to cross  $n$  vehicle lanes, its delay contains time for wait signal and conflict with vehicle.

Pedestrian average delay  $d_{a2}$  at large intersection,

$$d_{a2} = \frac{1}{Q_{a2}} \sum_{i=1}^{Q_{a2}} \left( \sum_{k=n_1(-n_2)}^{-n_2(n_1)} d_{a2,i}^k + t_i \right)_{meet \{S_2(PY)|S_2\}} \quad (23)$$

where  $d_{a2,i}^k$  is the delay of  $i$  crossing  $Ln_k$ ,  $s$ ;  $Q_{a2}$  is the pedestrian volume, ped/h.

Vehicle average delay  $d_{b2}$  at large intersection,

$$d_{b2} = \frac{1}{Q_{b2}} \sum_{k=-n_2}^{n_1} \sum_{j=1}^{Q_{b2}^k} (d_{b2,j}^k + t_j)_{meet \{S_2(SY), S_2(HY)|S_2\}} \quad (24)$$

Assumed  $\eta$  is the carrying ratio (including driver), ped/veh. Total delay of pedestrian and vehicle  $D_2$ ,

$$D_2 = \sum_{i=1}^{Q_{a2}} \left( \sum_{k=n_1(-n_2)}^{-n_2(n_1)} d_{a2,i}^k + t_i \right) + \eta \sum_{k=-n_2}^{n_1} \sum_{j=1}^{Q_{b2}^k} (d_{b2,j}^k + t_j)_{meet \{S_2(PY), S_2(SY), S_2(HY)|S_2\}} \quad (25)$$

Accordingly, average delay of pedestrian and vehicle  $d_2$ ,

$$d_2 = \frac{1}{Q_{a2} + \eta Q_{b2}} \left( \sum_{i=1}^{Q_{a2}} \left( \sum_{k=n_1(-n_2)}^{-n_2(n_1)} d_{a2,i}^k + t_i \right) + \eta \sum_{k=-n_2}^{n_1} \sum_{j=1}^{Q_{b2}^k} (d_{b2,j}^k + t_j) \right)_{meet \{S_2(PY), S_2(SY), S_2(HY)|S_2\}} \quad (26)$$

In this model,  $d_2$  is impacted by traffic conditions, such as  $Q_a$ ,  $Q_b$ ,  $n$ ,  $T$  and geometry conditions, such as  $l_b$ ,  $L_b$ ,  $h_0$ ,  $l_m$ . More importantly, it is related with  $S_2$  and its parameters, such as  $v_a$ ,  $v_b$ ,  $Y_{a-lb}$ ,  $Y_{a-lr}$ ,  $Y_{b-sy}$ ,  $Y_b$ .



$h_y, Y_0, Y'_0$ .

## 6. Case study

Taken the westbound of a intersection at Beijing as research object, the roads are urban trunk road and heavy traffic. The pedestrian and vehicle volumes at 3 periods are investigated, seen Table 2. Its signal timing are shown Fig. 4 signal cycle is 100 s.

Table 2. Pedestrian and vehicle volumes of eastbound at signalized intersection

period	Pedestrian volume (ped/h)			Vehicle volume(veh/h)						
				Exit way			Entrance way			Sum
	$Q_{a2}^{\uparrow}$	$Q_{a2}^{\downarrow}$	$Q_{a2}$	$Q_{b2}^3$	$Q_{b2}^2$	$Q_{b2}^1$	$Q_{b2}^{-1}$	$Q_{b2}^{-2}$	$Q_{b2}^{-3}$	$Q_{b2}$
a.m. peak	592	601	1293	558	766	532	355	333	445	2988
noon	292	414	706	147	365	140	162	370	117	1300
p.m. peak	536	538	1074	367	608	350	323	528	390	2566

Note: 2009.9.29. a. m. peak (7:00-9:00), noon (11:00-13:00), p. m. peak (17:00-19:00).

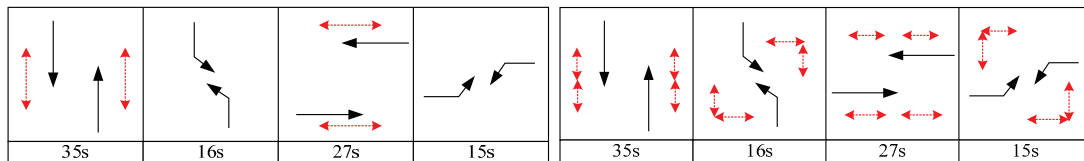


Fig. 4. Signalized timing (a) once crossing; (b) under twice crossing

Simulation is accomplished by VISSIM. Its parameters are shown Table 3.

Table 3. Simulating parameters of signalized intersection

parameters	unit	value	parameters	unit	value	parameters	unit	value
$l_m$	m	3.5	$n_1, n_2$	-	3	$h_0$	m	3.0
$l_a$	m	0.8	$Y_a$	m	0.85	$B_0$	m	1.5
$l_b^*$	m	1.8/2.5	$Y_0=Y_{b-hy}$	m	2.0	$v_a$	m/s	1.3
$L_b^*$	m	4.5/12.0	$Y_{b-sy}$	m	24.6	$v_b$	m/s	8.4
$\eta^{**}$	ped/veh	1.4/1.4, 75.0/40.0	$Y'_0$	m	1.5	$v'_b$	m/s	4.2

The inputs of VISSIM simulation include traffic volume and parameters shown as Table 2 and Table 3. The parameters such as yield distances and positions are the basement of behavior judgment rules. The delay values can be put out by the VISSIM software, in the paper,  $d_{U2D}$ 、 $d_{U2D}$ 、 $d_{a2}$  at 3 periods, a.m. peak, noon, p.m. peak of the intersection westbound under the once and twice pedestrian crossing. So does the  $d_{b2}$ . At last, the veh-ped system delays are obtained and shown as Figure 5.

Due to the vehicles flow, at the once pedestrian crossing, pedestrian average delay  $d_{a2}$ , vehicle average delay  $d_{b2}$  at peak time are bigger than ones at noon.  $d_{a2}$  at a.m. peak time is 1.9 times than one at noon, the value for  $d_{b2}$  is 2.3. at the twice pedestrian crossing, the situations are similar. Comparing the types of pedestrian crossing, for once speaking, pedestrian delay turns big due to he must wait at the center of road ( increased 40s/ped at 3 periods), but vehicle delay turn small due to the reduced conflicts at twice



pedestrian crossing (decreased 22.0s/veh(35.4%) at a.m. and 18.0s/veh(35%) at p.m.).

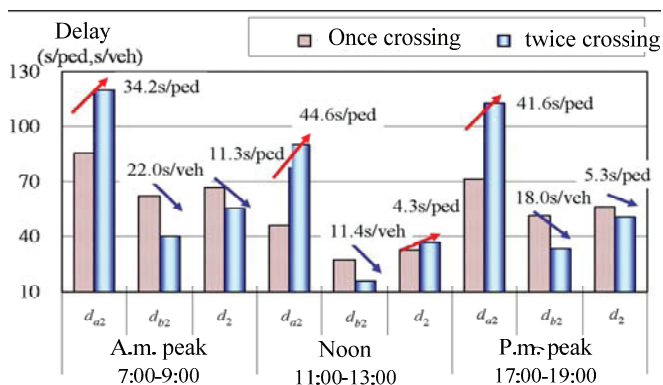


Fig. 5.  $d_{a1}$ ,  $d_{b1}$  and  $d_1$  of signalized intersection with different crossing types

For the veh-ped system delay  $d_2$  speaking, at twice pedestrian crossing, system operation is better than at once pedestrian crossing. At the a.m. and p.m. peak time,  $d_2$  are 55.4s/ped and 50.4s/ped for at twice pedestrian crossing, reduced 16.8% and 9.5% separately to once pedestrian crossing. Remarkable, the values at noon are increased 12.9% from 32.4s/ped to 36.6s/ped.

## 7. Conclusions

The pattern of twice pedestrian crossing has good benefit for urban traffic operation efficiency. Pedestrian and vehicle behaviors are described and conflict mechanisms at once/twice pedestrian crossing are analyzed at large intersection. Based on the pedestrian factors and conflict areas, used the area occupied rule, average delay model is established. At last, taken an intersection in Beijing as objects, vehicle, pedestrian and veh-ped delays are simulated.

(1) There at 3 pedestrian crossing behaviors, Park Yield, No Yield and No Conflict, 4 vehicle behaviors, Soft Yield, Hard Yield, No Yield and No Conflict. So, there are 4 conflict scenes at crosswalk. Vehicle and pedestrian behavior judgment rule are concluded.

(2) The reasons that lead to pedestrian and vehicle delays at 3/4 signal phrases are insufficient pedestrian crossing time. The pedestrian delay model, vehicle delay model and veh-ped delay model are established, then average veh-ped system delay model based on the once/twice pedestrian crossing are built.

(3) Comparing with once pedestrian crossing, system operation and vehicle delay are better except the pedestrian delay at twice pedestrian crossing. Simulation results show that system delays are reduced 16.8% and 9.5% separately to once pedestrian crossing, vehicle delay turn small due to the reduced conflicts (decreased 35.4% at a.m. and 35% at p.m). but pedestrian delay turns big (increased 40s/ped at 3 periods).

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